STUDY OF MULTIPLE OPTICAL TRANSITIONS IN ^{87}Rb USING LASER DIODES

C.L.J. Newton and H.G. Robinson
Physics Department, Duke University, Durham, N.C. 27706

ABSTRACT

Recent work with laser diodes has indicated their potential usefulness in optically pumping atomic frequency standards. We consider various optical pumping schemes for ^{87}Rb incorporating such light sources at two D1 frequencies for experimental situations of either evacuated wall-coated cells or atomic beams. Numerical integration of rate equations governing the level populations with arbitrary pumping light choices of intensity, D1 hyperfine transition(s), and polarization and subsequent calculation of scattered light provide a simplified 0-0 hyperfine signal analysis. By frequency modulating one laser diode, we have excited two optical transitions in an evacuated wall-coated cell and observed a large $\Delta m_F=1$ hf signal.

INTRODUCTION

The demonstration of ^{87}Rb hyperfine transitions as narrow as 10 Hz (FWHM) in an evacuated wall-coated cell[1] led to our interest in various schemes for optically pumping and detecting the $(F,m_F)=(2,0)\leftrightarrow(1,0)$ hyperfine "clock" transition. Recent work with laser diodes has indicated their potential usefulness in optically pumping frequency standards.[2,3] The spectral width obtainable from such diodes can be considerably less than the Doppler width of the D1 transition for room temperature ^{87}Rb, and initially we model this light source as a delta function in frequency which can be tuned to any of these optical transitions. In the case of an evacuated cell, the primary light-atom interaction is in the cell volume. This is a free-space interaction so that no mixing in the excited $^2P_{1/2}$ state occurs. In this sense, the atomic beam and evacuated wall-coated cell are quite similar. This is in contrast to the case of the buffer gas filled cell where mixing does occur in the excited state. The wall-coating reduces relaxation at the wall so that an atom may suffer many wall collisions before having its quantum state severely perturbed. As a result, the atom can undergo an optical pumping process (i.e., a re-distribution of ground state level populations by scattering light of specific polarizations and frequencies) extending over many wall collisions.

RATE EQUATION CALCULATIONS

Rate equations are written for the populations of the eight m_F sublevels of the $^2S_{1/2}$ electronic ground state of ^{87}Rb using electric dipole transition

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1982**	2. REPORT TYPE	3. DATES COVERED **00-00-1982 to 00-00-1982**
4. TITLE AND SUBTITLE **Study of Multiple Optical Transitions in 87Rb Using Laser Diodes**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Duke University,Physics Department,Durham,NC,27706**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the Fourteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Greenbelt, MD, 30 Nov ? 2 Dec 1982

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

matrix elements to describe the various leaving and entering rates. Such equations are well-known from early optical pumping experiments[4] and have recently been used in the analysis of 0-0 hyperfine transitions in atomic beams of Cs and Rb.[5,6] Our specific interest at present deals with ^{87}Rb D1 optical transitions. The rate equations are put in a general matrix formalism which allows use of any combination of intensities and polarizations of the four hyperfine components of the D1 transitions. (These transitions are labeled as (F-F')=(1-1'),(1-2'),(2-1'), and (2-2') where the primed number indicates the $^2P_{1/2}$ state F-value and the unprimed number, the corresponding value for the $^2S_{1/2}$ state. Thus pumping using various frequencies and Δm_F selection rules can be investigated. The limiting case of no T_1 relaxation is treated. It is a reasonable approximation in view of the long relaxation time attained in the wall-coated cell and the relatively high intensity available from the laser diode. Numerical integration by computer gives the time evolution of the level populations. The starting distribution assumes equal populations in each of the eight m_F-sublevels.

When a microwave-induced hf transition is present, the rate equations are modified by adding a term to the affected levels equal to a fixed fraction of the 0-0 level population difference. The "resonant signal" is taken as the difference between the total scattered photon flux under conditions of level population equilibrium when the mw power is on and the flux when the mw power is off. Other detection schemes are possible; we have chosen this method mainly for its simplicity and ease in making a relative comparison between several pumping cases. No attempt is made to consider optimal adjustment of mw power. A weak mw perturbation is used to avoid saturation effects. The choice of intensities of the various pumping components affects the scattered light at population equilibrium and hence, affects the 0-0 signal size. Thus intercomparison of pumping/detection schemes is dependent on the relative intensities used. In this paper, we choose equal relative intensities for each applied primary pumping component, σ^+, σ^- or π. In an experimental situation, different effective intensities of the components could be produced.

The simple procedure outlined above permits a comparison of pumping schemes with regards to level populations and scattered light intensity changes as the "signal." However it does not address the issue of the 0-0 resonance resolution obtained for various pumping schemes. For this we would need a resonance lineshape calculation including linewidths and saturation effects as well as signal amplitude and background flux.

Large population differences are attainable using two appropriate optical frequencies for pumping. For example, with circularly polarized light directed along the magnetic field axis (Δm_F=+1), at frequencies (2-2') and (1-2'), all population is pumped into the $(F,m_F)=(2,2)$ ground state level. By frequency modulating one laser diode with a square-wave current, we were able to excite these two transitions and to demonstrate a large hf signal for the $(2,2)\leftrightarrow(1,1)$ transition in a 1.5G magnetic field.[7]

Three of the best pumping schemes investigated for observing the 0-0 hf transition are now presented. Figure 1a shows the time development of level populations for the case of two resolved optical frequency transitions driven simultaneously by 1) linearly polarized σ-light at the (2-2') frequency and 2) linearly polarized π-light at the (1-1') frequency. The first causes $\Delta m_F = \pm 1$ transitions, while the second, $\Delta m_F = 0$ transitions with $0 \rightarrow 0'$ excluded. In equilibrium, all population has been driven into the (1,0) level. This achieves one of the desirable conditions for efficient pumping/detection: namely, large difference of population between the levels specified by the mw transition.

If the laser source has a finite frequency width and the cell has the real Doppler width for the D1 transitions, then optical transitions to the F'=1 and 2 states of the $^2P_{1/2}$ state from a common F-value in the ground $^2S_{1/2}$ are not completely resolved. For example, the tail of the (2-1') transition overlaps the (2-2') transition center. The unintentional excitation of (2-1') when exciting (2-2') provides a depumping mechanism which reduces the 0-0 level population difference. An estimate of optical resonance overlap was made for an optically thin cell by taking the absorption lineshape to be Gaussian with Doppler width of 500 MHz and the laser lineshape to be Lorentzian with width 300 MHz. The convolution of these two functions gives an absorption curve which has a ratio of tail height to on-resonance height of ∿ 5% when the tail frequency corresponds to the hf separation in the $^2P_{1/2}$ state (∿818 MHz). Actually the laser linewidth is expected to be ≤100 MHz for which the tail-center overlap is ≤ 1%. However, the examples discussed will use a 5% overlap to emphasize the effect.

In Fig. 1b, the primary optical pumping transitions are the same as in Fig. 1a but now, in addition, light of 5% relative intensity is added at each of the (1-2') and (2-1') transitions. The relative $0 \rightarrow 0$ hf transition signals in these two cases are in the ratio ∿ 1.8:1.

As shown in Fig. 2a, all population can be pumped into the (2,0) level by using transitions (2-2')π and (1-1')σ. The effect caused by addition of 5% relative intensities at (2-1') and (1-2') is shown in Fig. 2b. The ratio of 0-0 hf signals for these cases is ∿ 2.1:1.

A third example uses (2-2')π and (1-2')π-pumping radiation. See Fig. 3a and 3b where again an additional 5% relative intensities have been used at the (2-1') and 1-1') transitions. The ratio of 0-0 hf signals for these cases is ∿ 2.1:1.

An rf plasma excited Rb lamp with ^{85}Rb filtering is modeled by using unpolarized σ light with primary pumping transitions at (1-2') and (1-1') and secondary transitions (2-2') and (2-1') at 10% relative intensities. Figure 4a gives the level population history. In Fig. 4b we use linearly polarized π-radiation for pumping. The ratio of the respective 0-0 hf signals is ∿ 0.7:1.

An intercomparison of the 0-0 signals for Figs. 1a, 2a, 3a, and 4a relative to Fig. 4a gives the ratios 20:22:30:1. Differences in the rate of approach to equilibrium are evident from the figures. The case presented in Fig. 3 is the simplest from an experimental viewpoint since only one polarization and direction of propagation of light is required.

Several pumping schemes have been considered which show the possibility of obtaining a large 0-0 population difference with relatively large hf transition signals. Doppler linewidth and laser linewidth were treated to show effective depumping resulting in a reduced population difference and a larger background of scattered light intensity. The atomic beam method can take advantage of the much reduced effective Doppler width to avoid depumping. For either beam or evacuated cell, substantial improvement over conventional Rb lamp pumping is expected for the parameters discussed. We are actively pursuing an experimental comparison with these calculations.

REFERENCES

1. H.G. Robinson and C.E. Johnson, Appl. Phys. Lett. 40, 771 (1982.

2. L.L. Lewis and M. Feldman, Proc. 35th Ann. Symposium on Freq. Control, U.S. Army Electronics Command, Fort Monmouth, N.J., 612 (1981).

3. C.H. Volk, J.C. Camparo, and R.P. Frueholz, Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Greenbelt, Maryland, December 1-3, 1981.

4. W. Franzen and A.G. Emslie, Phys. Rev. 108, 1453 (1957).

5. P. Cerez and F. Hartmann, IEEE J. Quantum Elec. QE-13, 344 (1977).

6. M. Feldman, J.C. Bergquist, L.L. Lewis, and F.L. Walls, Proc. 35th Ann. Symposium on Freq. Control, U.S. ARmy Electronics Command, Ft. Monmouth, N.J., 625 (1981).

7. The laser for this experiment was kindly supplied by L.L. Lewis, Time and Frequency Division, National Bureau of Standards.

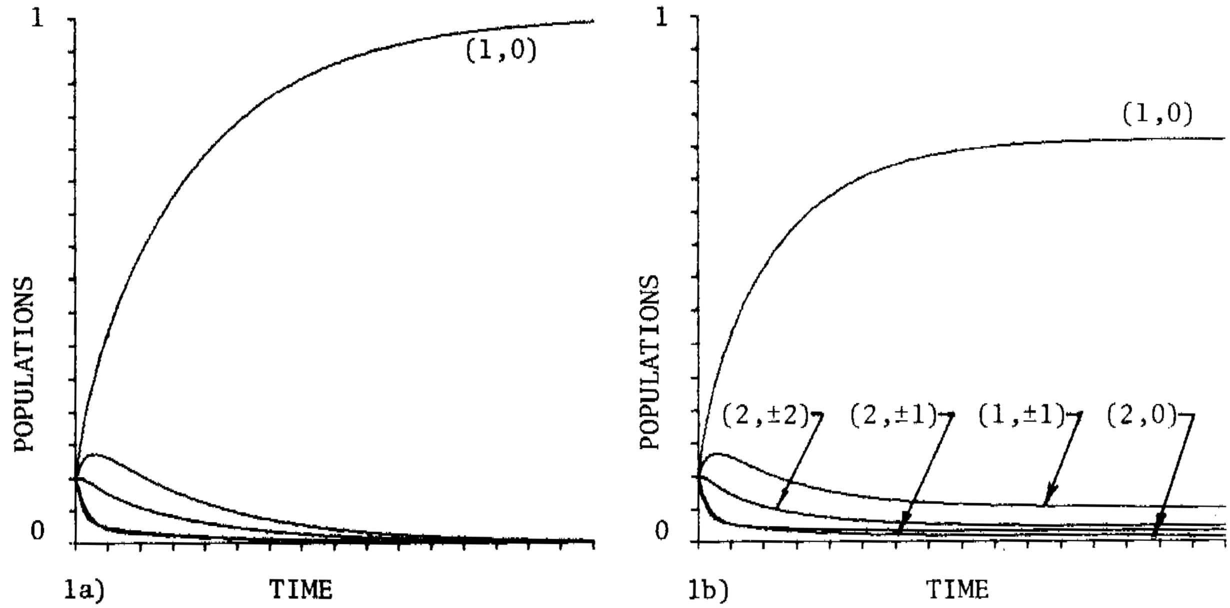


Figure 1. Level populations as a function of (arbitrary) time when pumping with (2-2') σ-light and (1-1')π-light. Completely resolved optical transitions are treated in a "a" while in "b", an additional 5% excitation is assumed for each of the (2-1') and (1-2') transitions.

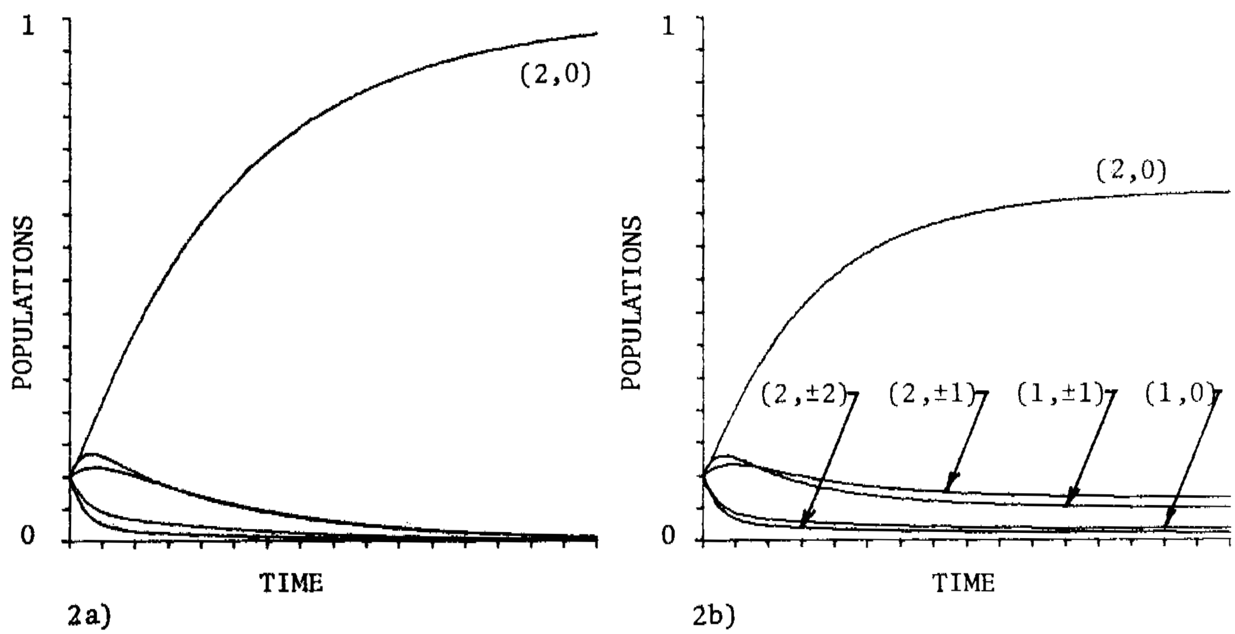
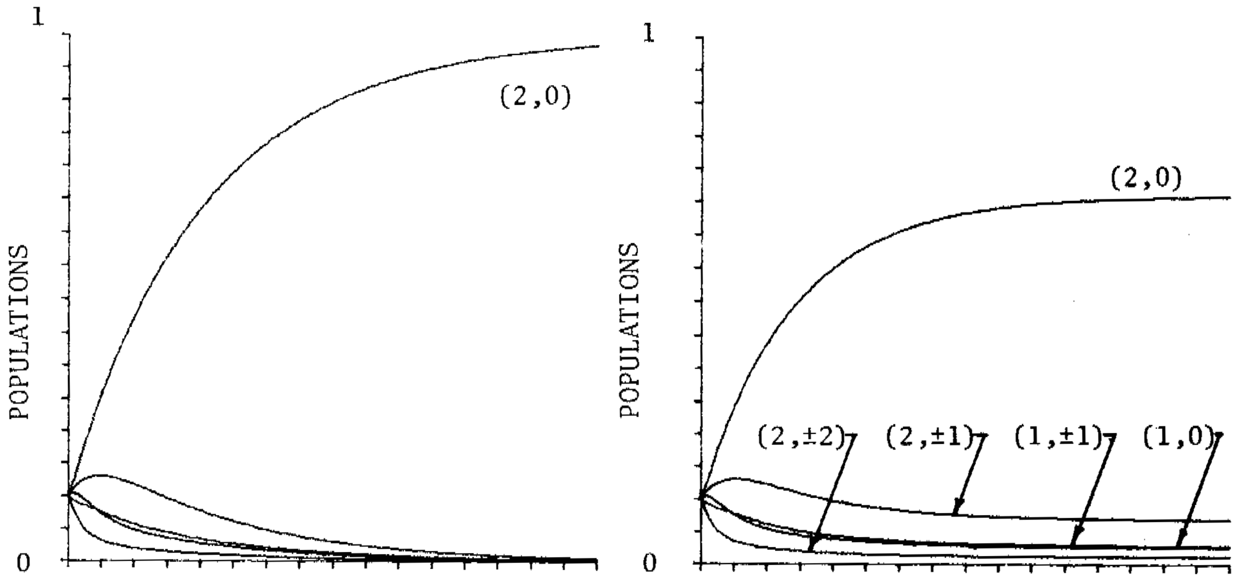
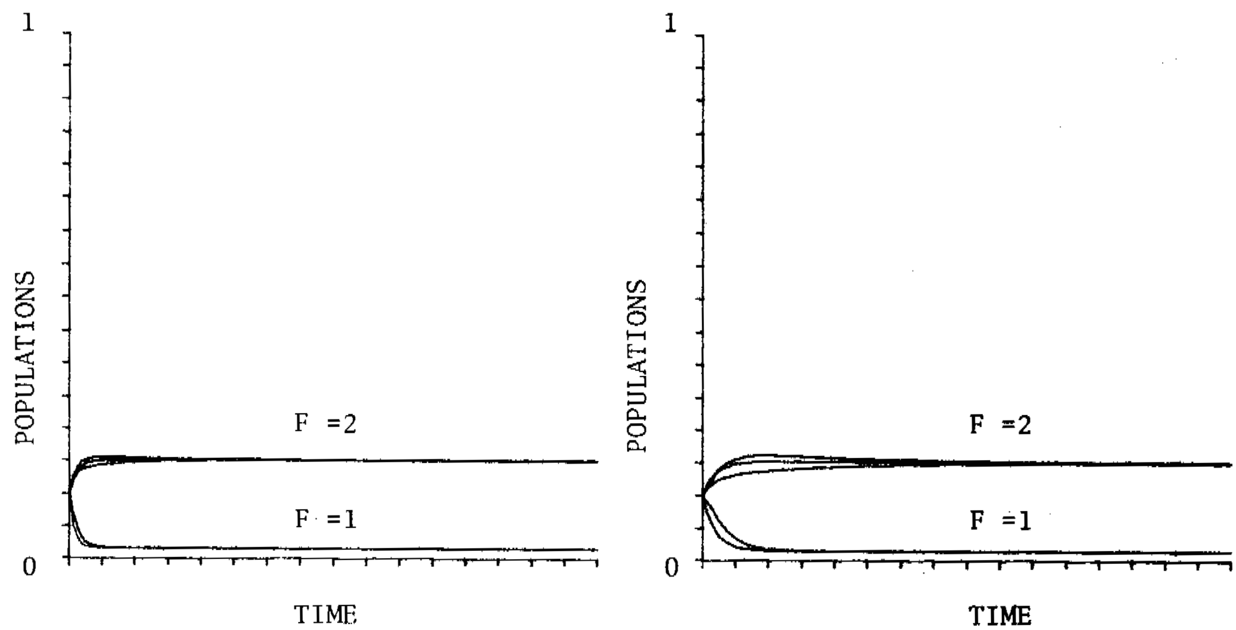


Figure 2. Time history of level populations when pumping with (2-2') π-light and (1-1') σ-light. In "b" an additional 5% excitation is assumed for each of the (2-1') and (1-2') transitions.



3a) 3b)

Figure 3. Time history of level populations when pumping with (2-2')π light and (1-2') π-light. In "b" an additional 5% excitation is assumed for each of the (2-1') and (1-1') transitions.



4a) 4b)

Figure 4. Time history of level populations when pumping with modeled Rb plasma lamp. Primary pumping is at (1-2') and (1-1') transitions with an additional 10% excitation at each of the (2-1') and (2-2') transitions. In "a" σ-light is used while in "b" π-light is used.

QUESTIONS AND ANSWERS

PROFESSOR ALLEY:

Could you tell us the state of the experiments please, Hugh?

MR. ROBINSON:

Yeah, Carroll. The experiments are in a state where we need some research funding. We have a laser which has been loaned to us by Lyndon Lewis and we are now in the act of trying to get a light system so we can put the light in at right angles to the field. The apparatus that we have, is built specifically for the Delta M plus one transition or minus one circular of polarized light.

And we are accustomed to looking at Zeeman transitions and getting the light in perpendicular to the access just requires a little bit of effort and we're now undertaking that. So we hope to go ahead and do these experiments that we would like to see is some comparison with this theory.